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ABSTRACT

Magnetic resonance imaging (MRI) is a new technique that affords anatomic images in multiple planes and may provide information on tissue characterization. This document describes how MR images are obtained and discusses how they differ from those produced by x-rays. The major portion of this report covers a conference held in October, 1987, which was designed to deal with safety and efficacy of the MRI method. The report provides evidence that was presented at the conference regarding the following questions: (1) are there contraindications to or risks of MRI? (2) what are the technological advantages and limitations (and disadvantages of MRI)? (3) what are the clinical indications for MRI, and how does it compare to other diagnostic modalities? and (4) what are the directions for future research in MRI? (TW)

MAGNETIC RESONANCE IMAGING

National Institutes of Health
Consensus Development
Conference Statement

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Introduction

Magnetic resonance imaging (MRI) is a new and innovative technique that affords anatomic images in multiple planes and may provide information on tissue characterization. The first magnetic resonance image was published in 1973 by Lauterbur. Since that time, major technological advances, together with increasing clinical and investigative interest in the method, have been accompanied by the development of equipment that is now clinically applicable to man, with potentially great benefits in assessing pathophysiologic states.

The MR images are obtained by placing the patient or area of interest within a powerful, highly uniform, static magnetic field. Magnetized protons (hydrogen nuclei) within the patient align like small magnets in this field. Radiofrequency pulses are then utilized to create an oscillating magnetic field perpendicular to the main field, from which the nuclei absorb energy and move out of alignment with the static field, in a state of excitation. As the nuclei return from excitation to the equilibrium state, a signal induced in the receiver coil of the instrument by the nuclear magnetization can then be transformed by a series of algorithms into diagnostic images. Images based on different tissue characteristics can be obtained by varying the number and sequence of pulsed radiofrequency fields in order to take advantage of magnetic relaxation properties of the tissues.

Magnetic resonance images differ from those produced by x-rays: the latter are associated with absorption of x-ray energy, while MR images are based on proton density and proton relaxation dynamics. These vary according to the tissue under examination and reflect its physical and chemical properties.

In order to resolve issues regarding safety and efficacy, the Warren Grant Magnuson Clinical Center and the Office of Medical Applications of Research of the National Institutes of Health (NIH) convened a consensus conference on MRI on October 26, 27, and 28, 1987. The conference was cosponsored by the Division of Research Resources, the National Cancer Institute, the National Heart, Lung, and Blood Institute, the National Institute on Aging, and the National Institute of Neurological and Communicative Disorders and Stroke of the NIH; the Food and Drug Administration (FDA); and the National Institute of Mental Health.

At NIH, the Consensus Development Conference brings together investigators in the biomedical sciences, clinical investigators, practicing physicians, and consumer and special interest groups to make a scientific assessment of technologies, including drugs, devices, and procedures, and to seek agreement on their safety and effectiveness.

During the first day-and-a-half of the meeting, a Consensus Development panel and members of the audience heard evidence presented on the following questions:

- Are there contraindications to or risks of MRI?
- What are the technological advantages and limitations (disadvantages) of MRI?
- What are the clinical indications for MRI, and how does it compare to other diagnostic modalities?
- What are the directions for future research in MRI?

Members of the panel included representatives of internal medicine, neurology, neurosurgery, radiation oncology, radiology, clinical epidemiology, surgery, the law, and the hospital community.

The National Institutes of Health urges that this summary statement be posted, duplicated, and distributed to interested staff.

The invited speakers included physicists, biomedical scientists, reproductive scientists, and radiologists with extensive experience in MRI in all of the subspecialties of the field.

1.

Are there contraindications to or risks of MRI?

MRI is generally safe when used in accordance with the performance characteristics approved by the FDA. Risks are primarily related to the static and oscillating magnetic fields used in MRI. These fields are capable of producing adverse biologic effects at a sufficiently high exposure, but effects have not been observed at the levels currently employed in clinical practice.

The most important known risk is the projectile effect, which involves the forceful attraction of ferromagnetic objects to the magnet. Caution also must be exercised when there are ferromagnetic objects embedded in the patient, such as shrapnel, or implants such as pacemaker wires. MRI should not be performed on patients with cardiac pacmakers or aneurysm clips.

Biologic effects of static magnetic fields, such as ECG changes in T wave amplitude and magnetohydrodynamic flow effects, are transient. In the short-term studies reported thus far, these do not appear to be hazardous at field strengths below 2 tesla. A preliminary case-control study of male workers exposed to magnetic fields has shown no trends indicating a dose-response effect, but the number of subjects was small and the followup period short.

Rapidly changing gradient fields can induce electric currents in conductive tissues. Recent studies indicate no interference with cardiac function or nerve conduction at 2 to 7 tesla. The exposure levels approved by the FDA, which are below those that would induce neuromuscular stimulation, are believed to provide a wide margin of safety in this respect.

Heating may occur in tissues as a result of resistive losses due to circulating currents from radiofrequency coils. High-field scanners are more likely to cause measurable temperature elevations than low-field devices. Although no adverse effects have been observed at FDA-approved absorption rates, care must be taken with patients whose heat loss mechanisms are impaired and with hyperpyrexic individuals. Pulse sequences should be modified to prevent excessive heat buildup, particularly in warm and humid environments.

Caution must be exercised in the MRI examination of infants, patients requiring monitoring and life-support systems, and patients who are pregnant. Although there is no evidence that magnetic and electric fields associated with MRI interfere with human development, *in vitro* studies and theoretical predictions raise the question of whether exposure might pose risks to the developing embryo and fetus. Therefore, MRI, as with all interventions in pregnancy, should be used during the first trimester only when there are clear medical indications and it offers a definite advantage over other tests.

2.

What are the technological advantages and limitations (disadvantages) of MRI?

Advantages

MRI provides information that differs from other imaging modalities. Its major technological advantage is that it can characterize and discriminate among tissues using their physical and biochemical properties (water, iron, fat, and extravascular blood and its breakdown products). Blood flow, cerebrospinal fluid flow, and contraction and relaxation of organs, both physiologic and pathologic, can be evaluated. Because calcium emits no signal on spin echo images, tissues surrounded by bone, such as the contents of the posterior fossa and the spine, can be imaged, and beam hardening artifacts are avoided. MRI produces sectional images of equivalent resolution in any projection without moving the patient. The ability to obtain images in multiple planes adds to its versatility and diagnostic utility and offers special advantages for radiation and/or surgical treatment planning. Excellent delineation of anatomic structures results from inherent high levels of contrast resolution.

Para- and superparamagnetic contrast agents, which appear to be relatively nontoxic, will soon be available in the United States. These agents should permit evaluation of the integrity of the blood-brain barrier, the reticulo-endothelial system, and the extracellular space.

MR image acquisition does not use ionizing radiation, nor does it require iodinated contrast agents. Because it requires little patient preparation and is noninvasive, patient acceptability is high.

Disadvantages

The relatively slow scan acquisition time results in artifacts due to biological (physiological) motion, e.g., cardiac, vascular, cerebrospinal fluid pulsation, respiratory excursion, and gastrointestinal peristalsis. Technological advances now evolving, such as cine MRI, improved surface coils, respiratory, cardiac, and peripheral gating, chemical shift imaging, and fast scanning (gradient refocused images), may resolve many of these problems. Some patients, particularly acutely ill patients, cannot cooperate and movement artifacts result. Patient throughput is slow compared with other imaging modalities.

Because of the small bore of the magnet, some patients experience claustrophobia and have difficulty in cooperating during the study. Some obese patients cannot be examined.

The strong static magnetic field, which interferes with the proper functioning of the usual life-support equipment, and the small bore of the magnet make it difficult or impossible to examine some critically ill patients. Patients with pacemakers and ferromagnetic appliances cannot be studied. MRI units require careful siting and shielding.

While the appearance of calcium as a signal void provides some advantages, it also limits the ability to detect pathological calcification in soft tissues and tumors, and pathological changes in cortical bone are poorly depicted, using routine spin echo techniques. Other imaging sequences may permit visualization of some of these lesions.

Presently, contrast agents to enhance the MR images are not approved for general use in the United States. Greater technological expertise is required for utilization of MRI than for most other imaging modalities. These factors limit the present application of MRI.

MRI equipment is expensive to purchase, maintain, and operate. Hardware and software are still being developed.

3.

What are the clinical indications for MRI, and how does it compare to other diagnostic modalities?

MRI is an evolving technology that in most instances has been evaluated by small descriptive studies rather than by large, carefully designed, prospective studies. Some of our judgments about the role of MRI relative to other imaging modalities are based on less rigorously designed studies than are desirable. For those clinical situations where MRI can potentially replace other procedures, especially invasive ones, these judgments should be verified by additional prospective studies. Furthermore, when other new, costly, or invasive imaging modalities are introduced in the future, considerable attention should be paid initially to the types of clinical problems that should be studied first, to the need for single or multi-institutional studies, to the timing of the evaluations, to the requirements for interpretive expertise, and to the potential sources of funding for such evaluations. A consensus conference might be a suitable vehicle for such deliberations.

The panel took the position that the diagnostic capability of MRI relative to those of its competing modalities was the most important endpoint to be assessed at this time. It should be recognized that an experimental approach that optimizes the attainment of diagnostic information cannot readily provide simultaneous information on the effect of MRI on other indices such as patient management and patient outcomes. Finally, it deserves emphasis that the panel focused on clinical efficacy and not on cost considerations.

The Brain

Brain Tumors

MRI is a superb method of studying brain tumors because of the excellent contrast resolution, easy multiplanar imaging, and absence of artifacts. MRI and CT are roughly equivalent for detection of most brain tumors. Because of the absence of bone artifacts, as seen on CT, MRI is superior at the vertex, in the posterior fossa, near the walls of the middle fossa, at the base of the skull, and in the orbit. CT is superior to MRI for detection of meningioma but requires contrast enhancement. MRI performance will be improved further by the use of contrast-enhancing agents.

Gliomas and metastases. Supratentorial gliomas and metastases are detected by either MRI or CT. Secondary effects of the tumor, such as herniation, hydrocephalus, and volume displacement of adjacent tissues, are displayed well with both CT and MRI, although more anatomic information is available with multiplanar MRI. Tumor boundaries in gliomas and metastases may be obscured by extensive edema. Contrast-enhanced CT currently is better than unenhanced MRI for defining the gross margin between tumor and edematous brain. Neither method is definitive in establishing a tissue diagnosis. Calcification is better seen with CT. Contrast-enhanced CT better demonstrates subarachnoid spread from malignant tumors than MRI. MRI is especially effective in the demonstration of intratentorial tumors.

Meningiomas. The characteristic hyperdense appearance of these tumors on contrast-enhanced scans and the hyperostosis of underlying bone allow superior detection by CT. MRI may provide more information than CT about the effect of the tumor on adjacent structures.

Acoustic Neuromas. MRI demonstrates smaller tumors better than CT, without the need for intrathecal air or contrast material, but larger tumors are well visualized by both CT and MRI.

Pituitary Tumors. Both MRI and contrast-enhanced CT are effective in defining pituitary tumors, but MRI may provide more information about the precise extent of the lesions and their effect on adjacent structures. Early studies suggest that MRI may be superior for detection of intrasellar microadenomas. MRI appears to be somewhat better in the diagnosis of some other suprasellar tumors, primarily because of its multiplanar capabilities and the absence of bone artifacts.

Reexamination. The factors that dictate the use of MRI or CT as the original detection tool also apply to followup studies.

Nonneoplastic Disease

Any insult to the structural integrity of the brain associated with alteration in water content or myelin can be reflected in abnormal signal intensity on MRI. Thus, MRI is sensitive to the detection of a wide variety of nonneoplastic processes affecting the brain. In many instances, the sensitivity of MRI exceeds that of CT.

Ischemia. Within a few hours after vascular occlusion, detection and localization of cerebral infarction is possible with MRI, while CT (even with contrast enhancement) often yields equivocal or negative results in the first 24 to 48 hours. In the subacute and chronic stages of stroke, MRI and CT provide equivalent information.

Hemorrhage. Within the first 24 to 48 hours, acute intracranial hemorrhage, whether subarachnoid, intraparenchymal, or subdural, is not easily detected with MRI but is more reliably demonstrated on CT. The subacute hematoma (age 10 to 20 days) is readily detected on MRI, while it may be much less conspicuous on CT. Thus, the two modalities have complementary roles in detection of hemorrhage—CT is more sensitive in acute hemorrhage, while MRI is more sensitive in subacute hemorrhage. Unenhanced CT is often the preferred initial study in patients with stroke because of the clinical need to determine the presence of hemorrhage.

Arteriovenous Malformations. MRI is exquisitely sensitive to flowing blood and has proven particularly effective in the detection and localization of vascular malformations, including some "cryptic" malformations not evident on cerebral arteriography. Arteriography remains necessary for the pretherapeutic assessment of symptomatic malformations.

Trauma

In head trauma, MRI has proven useful in the detection of all types of intracranial hemorrhage, including hemorrhagic contusions and shearing injuries. During the first 1 to 3 days after injury, however, CT is preferable not only because examination time is shorter but also because hemorrhage at this time is more reliably demonstrated by CT.

Disorders of Myelination

Diseases associated with demyelination or dysmyelination are readily detected with MRI. MRI is recognized as the preferred and most sensitive imaging technique for the diagnosis of multiple sclerosis (MS), but MRI alone cannot establish a definite diagnosis of MS in the absence of strong clinical findings. MRI also exhibits greater sensitivity in the detection of radiation injury to the brain than does CT. However, in the followup of patients after radiation therapy or chemotherapy for malignant intracranial neoplasm, neither MRI nor CT permit differentiation of late radiation injury from recurrent tumor.

Dementia

The diagnosis of dementia requires a clinical neurological evaluation. In the assessment of dementia, either CT or MRI can be used to demonstrate remediable lesions. MRI demonstrates more lesions than CT in patients with multi-infarct dementia. In older individuals, however, often without dementia, MRI also demonstrates high signal areas in white matter on T2-weighted images of uncertain clinical significance.

Infection

MRI demonstrates areas of cerebritis and abscess formation in a manner similar to CT. White matter edema associated with inflammation is readily detected by MRI and may allow earlier initiation of specific treatment in certain illnesses such as herpes simplex encephalitis.

Head and Neck

In the detection, localization, and treatment planning of head and neck tumors, MRI offers an advantage over CT due to its multiplanar capabilities, tissue characterization potential, and the absence of bone and teeth artifacts. MRI affords ready distinction of vessels from lymph nodes. MRI also depicts the contents of the orbit.

The Spine

Surface coils constitute an integral part of the MRI examination of the spine.

Tumors

MRI of the spinal canal has the advantage over myelography of direct, noninvasive visualization of the spinal cord rather than merely outlining its margins. MRI is capable of demonstrating the entire spinal cord and of differentiating solid from cystic intramedullary tumors. Indications for myelography have decreased considerably, and it may become obsolete in the future with the wider availability of high-quality MRI. An example of this is the use of MRI for the diagnosis and localization of acute spinal cord compression. Intradural extramedullary tumors are best demonstrated by MRI or myelography.

Syringomyelia

MRI is the diagnostic method of choice and is considered to be superior to both myelography and CT.

Degenerative Disc Disease

MRI is equivalent to CT myelography in the evaluation of herniated disc at the cervical and thoracic levels and is as good as or better than myelography. At the lumbar level, MRI is better than or equal to CT and is more accurate than myelography. In spinal stenosis, MRI and CT are roughly equivalent in diagnostic information and less invasive than myelography. CT myelography provides the greatest diagnostic accuracy for cervical radiculopathy due to hypertrophic degenerative changes.

Trauma

When the patient's condition allows, MRI demonstrates the altered relationship between vertebral bodies, discs, spinal cord, and nerve roots. It is less applicable to the study of spinal stability and the integrity of articular facets than CT or conventional radiography.

Congenital Disorders

Spinal cord abnormalities associated with congenital spinal dysraphism are most advantageously studied by MRI.

Infection

MRI and radionuclide scans are more sensitive than CT for the early detection of osteomyelitis.

The great accuracy of both MRI and CT in defining spinal anatomical changes poses a particular challenge to clinicians. Correlative clinical studies to relate these changes with patients' symptoms and outcome of therapy are urgently needed.

The Cardiovascular System

MRI is particularly valuable as a technique for imaging the heart and great vessels because flowing blood produces a unique signal. Therefore, no contrast medium is required to define the cardiac chambers and the lumen and location of the great vessels. Cardiac evaluation requires either ECG gated MRI or cine MRI.

Ischemic Heart Disease

At the present time MRI has limited usefulness in evaluating ischemic heart disease. It cannot substitute for coronary arteriography in defining coronary artery anatomy. It apparently can delineate infarcted myocardium and adjacent residual viable myocardium. With paramagnetic contrast media it may be possible to define regions of acute ischemia. Gated MRI can be used to delineate scarring caused by previous infarction, ventricular aneurysm, and chamber thrombi.

Cardiomyopathies

Gated MRI defines the endocardial and epicardial surfaces, making it possible to determine mural and septal thickness, ventricular volume, and performance. Two-dimensional echocardiography and radionuclide techniques provide information similar to MRI.

Valvular Heart Disease

The recent development of cine MRI, which permits rapid dynamic imaging, makes it possible to evaluate ventricular performance and to estimate the severity of valvular regurgitation. The relative values of 2-D and Doppler echocardiography, other noninvasive methods, and the cine MRI technique have yet to be determined.

Pericardial Disease

Gated MRI is being used to evaluate pericardial disease, but echocardiography remains the procedure of choice because of lower cost, portability, and availability.

Intracardiac and Paracardiac Masses

MRI depicts the pericardium, cardiac chambers and walls, and the great vessels in the mediastinum. For imaging of intracardiac and paracardiac masses, MRI appears to be superior to CT, although echocardiography remains the primary screening procedure for intracardiac masses.

Congenital Heart Disease

MRI, through definition of the cardiac chambers, great vessels, and flow patterns, represents an important noninvasive diagnostic imaging method in congenital heart disease. Because of the relatively long times required for MRI, ECG gating or cine MRI is important to optimize its value. Gated MRI is capable of defining many malformations of the cardiac chambers and the great vessels, such as transposition and pulmonary atresia. Two-D and pulsed Doppler echocardiography continue to be the primary initial screening techniques and provide information on pressure and flow in addition to cardiac anatomy.

Aorta

While CT has served as a screening method in aortic dissection, the anatomic findings required for surgery have been determined primarily by angiography. MRI permits visualization of the aortic root and detects intramural hemorrhage, wall separation, and intimal flap. It may improve the screening of suspected cases, but it is uncertain that it will obviate the need for contrast angiography. It permits the distinction between aortic dissection and aneurysm of the thoracic and abdominal aorta. CT scanning has been accurate in delineating aortic size, change in aneurysm dimensions, and aortic aneurysmal bleeding. MRI has a similar potential.

Thorax

Staging of Bronchogenic Carcinoma

MRI is comparable to CT in diagnosing mediastinal adenopathy. The current interpretive criteria for MRI (as based on node size) are derived from and are identical to those used for CT. MRI is superior to unenhanced CT, however, in evaluating hilar masses, and is equivalent to enhanced CT. Because CT can evaluate the mediastinum and the upper abdomen as well as the lungs and abdomen as part of one examination, it is currently the method of choice for staging bronchogenic carcinoma.

Evaluation of Mediastinal Masses

MRI, because of its multiplanar imaging potential, provides information for determining the anatomic relationship between mediastinal masses and the great vessels that is not always available with CT.

Evaluation of Parenchymal or Hilar Masses

CT is used for the detection of pulmonary nodules. In solitary pulmonary nodules, CT is preferred to MRI for assessing benignity. Because of the ability of MRI to visualize flowing blood, it is preferred to unenhanced CT for determining whether hilar or parenchymal masses are solid or vascular.

Liver

MRI is equivalent to contrast-enhanced CT in the detection of patients with metastases to the liver from carcinoma. The use of iodinated contrast agents may be avoided with MRI. Cysts and hemangiomas, two common benign lesions, are relatively well characterized by MRI.

Pancreas and Spleen

For evaluating lesions of the pancreas and spleen, CT is superior to MRI.

Kidney

Renal Masses

In detecting renal masses, MRI is apparently equivalent to CT, with specific limitations noted below. Cysts and angiomyolipomas can be characterized as with CT, and complicated cysts, containing hemorrhage, can be identified.

Benign tumors can be visualized but not reliably distinguished from malignant neoplasms.

Malignant tumors are identified and staged as with CT, but the limited ability of MRI to detect calcifications and define small tumors is a drawback. MRI is useful for demonstrating vascular invasion.

Thus, MRI may be used in selected cases when CT examination is equivocal or when iodinated contrast material is contraindicated.

Renal Transplants

The normal corticomedullary junction of the kidney is demonstrated with MRI. When the junction is not visualized, the diagnosis of graft rejection can be suggested. Although MRI is useful, Doppler ultrasound appears to be more sensitive and specific.

Adrenal Gland

MRI is equal to high resolution CT in visualizing the normal gland and in detecting lesions such as hyperplasia, adenoma, aldosteronoma, pheochromocytoma, and primary carcinoma, as well as metastasis. Pheochromocytomas have an MRI intensity pattern that seems to be characteristic. Furthermore, the diagnosis can be made without using contrast agents, to which patients sometimes react. Other lesions cannot be reliably characterized.

Female Pelvis

The uses of MRI in gynecologic disease are in the early stages of investigation, but the ability of the examination to depict anatomy in three orthogonal planes affords a potentially useful method of staging tumors and selecting and planning the treatment to be employed. MRI is not a screening modality and does not permit specific tissue diagnoses.

The application of MRI in high-risk obstetrical practice requires further exploration.

Carcinoma of Endometrium

MRI shows promise as a means of staging as compared to physical examination or CT. The choice of therapy may depend on tumor volume, site, and depth of myometrial invasion, all of which can frequently be demonstrated by MRI.

Carcinoma of the Cervix

The value of MRI in staging cervical carcinoma lies in its ability to demonstrate the tumor directly, to calculate its volume, and to evaluate extension to adjacent organs accurately. Although useful for staging in selected cases, it has no apparent advantage over CT in the detection of lymph node metastases.

In both endometrial and cervical carcinoma, the capacity of MRI to depict concomitant pelvic lesions adds to its value.

Male Pelvis

Prostate

While it does not permit reliable differentiation of prostatic carcinoma from benign prostatic hypertrophy, MRI represents a promising method for staging the extent of carcinomatous spread outside the capsule of the prostate gland and appears to be equivalent to CT in this regard. Metastases to regional lymph nodes appear to be detected by MRI and CT with equal efficacy.

Bladder

In staging bladder carcinoma, MRI cannot distinguish mucosal lesions from those with superficial muscular invasion, but it is effective in staging tumors that have invaded the deep muscle layers, the perivesical fat, and adjacent organs and lymph nodes. While no large prospective studies comparing MRI with CT are available, preliminary data indicate that tumor staging with MRI is as accurate as with CT.

Scrotum

In the scrotum, MRI permits distinction of intratesticular from extratesticular lesions. It appears to have no diagnostic advantage over ultrasound, except when examining the painful scrotum.

Rectum

The staging of rectal neoplasms as well as the differentiation of recurrent tumor from fibrosis in the rectal wall represents problems that require further study.

Musculoskeletal System

Surface coils are essential for adequate examination of many areas in the musculoskeletal system.

Joints

MRI demonstrates the articular cartilages as well as adjacent muscles and tendons. Because it is noninvasive, MRI may be preferable to arthrography and arthroscopy in the study of the knee. It is also useful for evaluation of the temporomandibular joint. The use of MRI in the examination of other joints requires further evaluation.

Marrow Space

MRI reflects changes in the marrow space by primary tumors and infection. The local extent of primary bone tumors can be staged best by MRI. Metastatic tumor can be demonstrated with MRI, which apparently is more sensitive than radionuclide bone scanning.

Aseptic Necrosis of Bone

MRI is superior to radionuclide imaging in the detection of the early changes. Preliminary data suggest that MRI is better than CT.

Soft Tissue Tumors

MRI provides important information regarding muscle, nerve, and vessel invasion or entrapment in malignant soft tissue tumors. A postoperative baseline MRI study can be helpful when the possibility of recurrence must subsequently be evaluated.

Trauma

Because of the excellent contrast resolution of soft tissues, MRI demonstrates muscle and ligament tears and hematomas well. This may be useful in following the evolution of these lesions.

Contrast Media for MRI

Contrast agents are currently being evaluated in laboratory and clinical studies. These agents, by altering inherent tissue response to magnetic fields, offer the promise of even greater sensitivity for detection and improved lesion characterization. They fall into two classes: *paramagnetic* materials, which have diagnostic properties similar to iodinated radiographic contrast agents, and even more potent *superparamagnetic* materials, which have a wide area of effect. Gadolinium (Gd) DTPA appears safer than iodinated contrast media.

Intravenous infusion of Gd-DTPA demonstrates breakdown of the blood-brain barrier on T1-weighted MRI studies, and such images permit improved definition of gross margins of tumor, abscess, or infarct. Outside the brain, the use of contrast-enhanced MRI may identify areas of altered circulation due to inflammation, other soft tissue injury, or neoplastic spread.

4.

What are the directions for future research in MRI?

The role of MRI in the management of the patient needs to be defined. What does it replace in existing diagnostic algorithms? To what is it complementary? For example, will the need for CT, ultrasound, and arteriography decrease? How does the information provided affect diagnosis, staging, therapy, and patient outcome? The answers to these questions will require well-designed and well-conducted studies comparing the efficacy of MRI with existing diagnostic techniques.

Positron emission tomography (PET) can spatially image metabolic processes. To what extent is MRI capable of fulfilling a similar function in regard to pH, blood flow, blood volume, and the metabolism of oxygen and glucose? Similarly, PET has been used to study neurotransmitters and their receptors; can MRI be applied for this purpose not only to the central nervous system but also to different membrane receptors in other organs?

Diagnostic imaging is concerned with detection, localization, and tissue characterization. MRI has been shown to be effective for all three but offers special promise for tissue characterization. Future potential for MRI includes nonproton imaging, for example, phosphorus and sodium. The combination of imaging with localized *in vivo* spectroscopy may yield fundamental information regarding the metabolic status of a particular organ or lesion. For example, phosphorus metabolite concentration may be measurable as a reflection of the state of oxygenation of the myocardium or of tumors. *In vitro* spectroscopy offers a method for examining biologic material of various types, for example, tissue fluids, pathologic specimens, and cells in culture.

Further exploration of the applications of MRI to the vascular system is required. It appears to have promise as a means of assessing peripheral venous disease noninvasively.

Although considerable development of equipment for MRI has occurred, there appear to be opportunities for enhancing both hardware and software. Improving the techniques of MRI includes the selection of the appropriate energy of the magnet, optimization of the magnetic field strength in use, the fabrication of efficient surface coils, the evaluation of new pulse sequences, and the development of computer software leading to the richer utilization of the available data.

Gadolinium DTPA has promise as a contrast agent for MRI. There should be an active search for and an evaluation of other classes of contrast agents applicable to MRI. Paramagnetic-labeled pharmaceuticals and monoclonal antibodies offer new opportunities for acquiring anatomic, physiologic, and pharmacologic information. For example, there are disorders characterized by qualitatively or quantitatively abnormal receptor sites that would lend themselves to study using these agents.

It appears that MRI is a safe modality for imaging. Nevertheless, there must be continuing investigation of its secondary effects such as local heating of tissues. This is necessary as higher field strengths and rapid imaging techniques are more widely utilized. There is a need for long-term studies of the potential somatic and genetic effects of magnetic resonance. These should consider not only the patient but also those individuals exposed occupationally.

Conclusion

MRI is an innovative technique that provides images of the body in many different planes and represents an extraordinary addition to our diagnostic armamentarium. The images generated vary according to the tissues examined and reflect their physical and chemical properties. It is noninvasive, appears to be relatively innocuous in clinical application, and involves no exposure to ionizing radiation.

Even in the short period of its use, it has proved to be unusually rewarding in the detection, localization, and assessment of extent and character of disease in the central nervous, musculoskeletal, and cardiovascular systems. In the brain, for example, it has a proven capacity to define some tumors and the plaques of multiple sclerosis provided by no other technique. It is a competing imaging method in the evaluation of many other organs. Additional prospective studies comparing MRI with other diagnostic methods are essential in those areas where the method has shown promise but where its precise role has not yet been defined. This consensus development conference does not purport to include all of the applications of MRI to the pediatric patient, a subject that will require separate consideration.

Although MRI can be used without contrast media, the information it generates can be augmented by contrast agents now being introduced.

The full potential of MRI has not been reached, and continuing refinement of equipment, contrast agents, and software may be anticipated. As higher magnet strengths and rapid imaging sequences are investigated, further study of the long-term biologic effects of magnetic fields is required.

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